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A Gibbs sampling disaggregation model for orographic precipitation

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ABSTRACT

Hydrological applications in complex topographic areas need high spatial resolution precipitation data. Some daily high-resolution products are now available for recent past data, even in complex terrain. While the spatial resolution of Regional Climate Models (RCMs) and operational meteorological models are becoming increasingly fine, there still exists a mismatch between the spatial resolutions of observed or estimated recent past data and simulated or forecasted precipitation.

Statistical disaggregation models can generate precipitation on a high-resolution grid using as input a mesoscale precipitation grid (e.g., RCM or meteorological grid). In this paper, a Gibbs sampling disaggregation model previously developed for flat areas is adapted to account for topography. Only one variable, the topographic anomaly, is added to the original model. The model is applied on a 300 km × 300 km area in the northwestern United States, covering the Olympic Mountains and the Cascade Range. Daily high-resolution precipitation data for the 2002–2005 period are used to estimate the model parameters. Using 750 days taken from the 2006–2008 period, 36, 52-km grid boxes are disaggregated on 4.3-, 8.7-, 13-, 17.3- and 26-km grids; each day being simulated nine times. Thank to the Gibbs sampling algorithm, the original model, which does not account for topography, is able to capture the mesoscale topographic structure of the daily precipitation, while the adapted model accounting for topography is better suited to recreate the local impact of topography on interannual means, interday standard deviation, and maximum values. The model outputs could be used by hydrological modelers who need high-resolution precipitation data in complex topographic area application.

1. Introduction

Precipitation in mountainous regions is characterized by higher spatial variations than those in flat valleys. These variations can play an important role on the hydrology of mountainous watersheds. High spatial resolution precipitation data are then required in these regions.

Weather radars or radar–raingauge composite data are used to produce maps of hourly or daily precipitation at high resolution (<5 km). However, for short and long term precipitation data, whether from Regional Climate Model (RCM) predictions or meteorological model forecasts, operational data are available at best at a resolution of 10 km (Maraun et al., 2010). While the resolutions of RCMs and meteorological models are continuously improving, the spatial resolution of observed data is also improving. It results that there will always be a mismatch between the spatial resolution available from recent past observed or estimated data and from meteorological forecasts or RCM predicted data. To perform the same hydrological applications for future data than for recent past data, RCMs or meteorological models precipitation data need to be spatially disaggregated.

Disaggregation produces precipitation fields on a finer grid than the original data. Disaggregation of RCM precipitation can be performed dynamically by running the model in a nested domain. Yu et al. (2002) performed a simulation using a 12-km resolution domain nested in a 36-km domain, the latter nested in a 108-km domain. Lakhtakia et al. (1999) disaggregated to a 4-km domain, but the results were not significantly better than those obtained with a 12-km domain to justify the additional computational time needed. In addition to the high computational requirements, a 4-km RCM simulation may be inaccurate if the physical parameterization is the same as that of a larger resolution such that of a 36-km simulation. Some physical processes may have a negligible impact at 36 km, but may become important at 4 km.

As an alternative dynamical model, orographic precipitation models (OPMs) simulate high-resolution precipitation field specifically in mountainous areas by taking into consideration the humidity lifting produced by the wind “hitting” a mountain (Sinclair, 1994; Hay, 1998; Hay and McCabe, 1998; Pandey et al., 2000). The lifting increases the cloud water density and parameters may be added to account for the time required for the conversion from cloud water to hydrometeors and for hydrometeor fallout

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(Smith and Barstad, 2004; Schuler et al., 2008). These models need to have as input the topography and atmospheric variables like atmospheric pressure, temperature, relative humidity, wind speed and direction at various altitudes (Hay and McCabe, 1998).

Statistical models have the advantage to be simpler and require less computational time. To spatially distribute point sources of precipitation data over a mountainous area, most authors hypothesize that precipitation linearly increases with altitude. Daly et al. (1994) used a simple linear regression on altitude, with point observations weights depending on seven variables, including their distance to the estimating point and the orientation of the terrain. Neilson et al. (2010) incorporated latitude in addition to altitude as well as Clark and Slater (2006) who also included longitude. Diodato (2005) performed cokriging with elevation and a topographic index as covariables. Since daily precipitation has a high spatial variability, a lot of these interpolation methods are accurate only on monthly, seasonal or annual timescales.

For future climate, point sources of precipitation data are not available. Interpolation of mesoscale gridded data, by considering the center of a grid box as a point source data, produces fields too smooth for daily precipitation compared to disaggregation. Several proposed disaggregation models in mountainous areas combined results from a cascade-based model, which accounts for the multifractal properties of precipitation (*e.g.*, Deidda et al., 2006), with temporal means of observed data to account for spatial heterogeneity. Jothityangkoon et al. (2000), Pathirana and Herath (2002), and Sharma et al. (2007) produced disaggregated fields by merging outputs from a cascade-based model (Over and Gupta, 1996) with the interannual monthly mean precipitation for each pixel of the disaggregated grid. Badas et al. (2006) proceeded in a similar manner and presented the long-term mean precipitation as a linear function of elevation. Guan et al. (2009) produced disaggregated fields using a weighted mean of outputs from a cascade-based model (Gupta and Waymire, 1993) and an estimated precipitation value derived from a deterministic linear equation accounting for longitude, latitude, altitude and orientation of the slope. Bindlish and Barros (2000) used a statistical/dynamical procedure. They disaggregated a 4-km field into a 1-km field by generating a Brownian noise field and by simulating an uplift wind field with a kinematic flow model.

Markovian models, which explicitly account for the precipitation values in the neighboring pixels, have been applied for disaggregation, but to a lesser extent (see *e.g.* Wheater et al., 1999; Chandler et al., 2000; Mackay et al., 2001; Allcroft and Glasbey, 2003). These models are appealing because they are more capable of producing realistic spatial correlation compared to cascade-based models, which tend to produce discontinuities between adjacent pixels (see *e.g.* Ahrens, 2003; Sharma et al., 2007). Gagnon et al. (in press) proposed a Gibbs sampling-based disaggregation model which is able to produce daily precipitation with realistic spatial structures while being conceptually simple. The model accounts for the type of event through the atmospheric variable CAPE, the convective available potential energy. The model was applied in southeast United States, where highly convective events are frequent, but where topography does not vary considerably. To our knowledge, Markovian disaggregation models have never been applied in complex topographic areas.

The objective of the present work is to adapt the model developed by Gagnon et al. (in press) to account for orographic precipitation. The model must generate realistic precipitation fields (*i.e.* fields with coherent spatial correlation with a high degree of anisotropy), while retaining the conceptual simplicity of the original model. The model is applied to disaggregate daily precipitation (2006–2008) of 36 grid boxes located in the northwest United States; from a 52-km grid to several finer grids (4.3-, 8.7-, 13-, 17.3- or 26-km resolutions).

Section 2 presents the study area along with the input data used. Sections 3 and 4 describe the two disaggregation models used, that are without and with a parameter accounting for topography. Section 5 introduces the disaggregation results for the 2006–2008 period. Discussion of these results is provided in Section 6.

2. Data

This section presents the precipitation, elevation and atmospheric data used. First, the study area is described.

2.1. Study area

The study area is a region of about 300 km × 300 km located in the western part of Washington State and the extreme northwest part of Oregon (Fig. 1). The Olympic Mountains, in the northwestern part, and the Cascade Range, from the north-east to the south-west, characterized this region. Mount Rainier is the highest point with an elevation of 4392 m. This region has an oceanic climate, except east of the Cascade Range, where the climate is dryer (Western Regional Climate Center, 2002). For the study area and the driest and wettest years, precipitation estimates from the 2002 to 2008 dataset have annual averages of 1069 mm (2008) and 1586 mm (2006), respectively. Interannual daily means on the 4.3-km grid (2002–2008) varied from 0.3 to 14.7 mm within the area, illustrating that the topography affects the spatial distribution of precipitation. About 80% of the annual precipitation falls between November and April; snow is frequent for the highest elevation points.

2.2. Precipitation data

Daily precipitation data from the *National Center for Environmental Prediction* (NCEP) Stage IV analysis (Lin and Mitchell, 2005) are used in the present work. This product maps, on a high-resolution grid (about 4.3 km in the study area) covering the continental United States, precipitation estimates of the 12 River Forecast Centers (RFCs).

The study area is covered by the northwest RFC (NWRFC). In this area, it is problematic to get quantitative radar estimates especially because of beam blockage and bright band. This is why the daily precipitation values are estimated from the Parameter-elevation Regressions on Independent Slopes Model (PRISM; Daly et al., 1994; Di Luzio et al., 2008). PRISM interpolates raingauge data assuming that precipitation increases linearly with elevation. As classical interpolation methods, for a given point, the nearest stations have higher weights, but other weighting variables are used to account for the physics of precipitation, such as the distance to the coast, the orientation of the pixel, the vertical layer and the effective terrain. Quantitative radar estimates are not used in the mapping procedure. Nevertheless, radar data are used indirectly to monitor training of echoes and spatial distribution (Alex Orr, NWRFC, personal communication).

Daily precipitation data are rounded off to the nearest integer (mm/day). Seventy-two by 72 4.3-km pixels are analyzed (Fig. 1). Parameter estimation is done on the 2002–2005 data. Then, 750 days receiving precipitation (either solid or liquid) from 2006 to 2008 are used for the validation of the disaggregation model. Thirty-six (6 × 6) 52-km grid boxes are created by the aggregation of each block of 12 × 12 pixels. The two models analyzed disaggregate these boxes and the resulting fields are compared with the reference data.